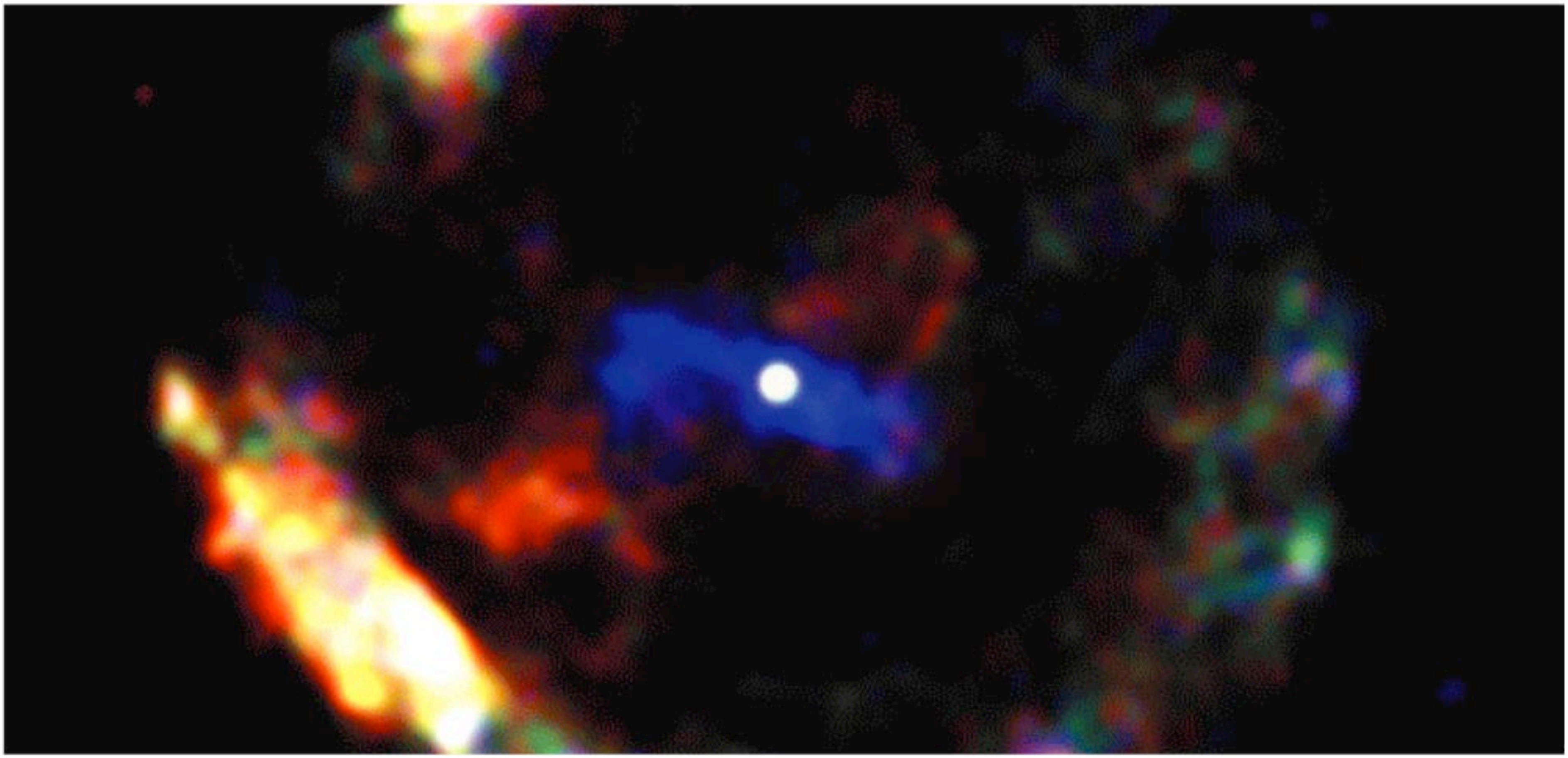
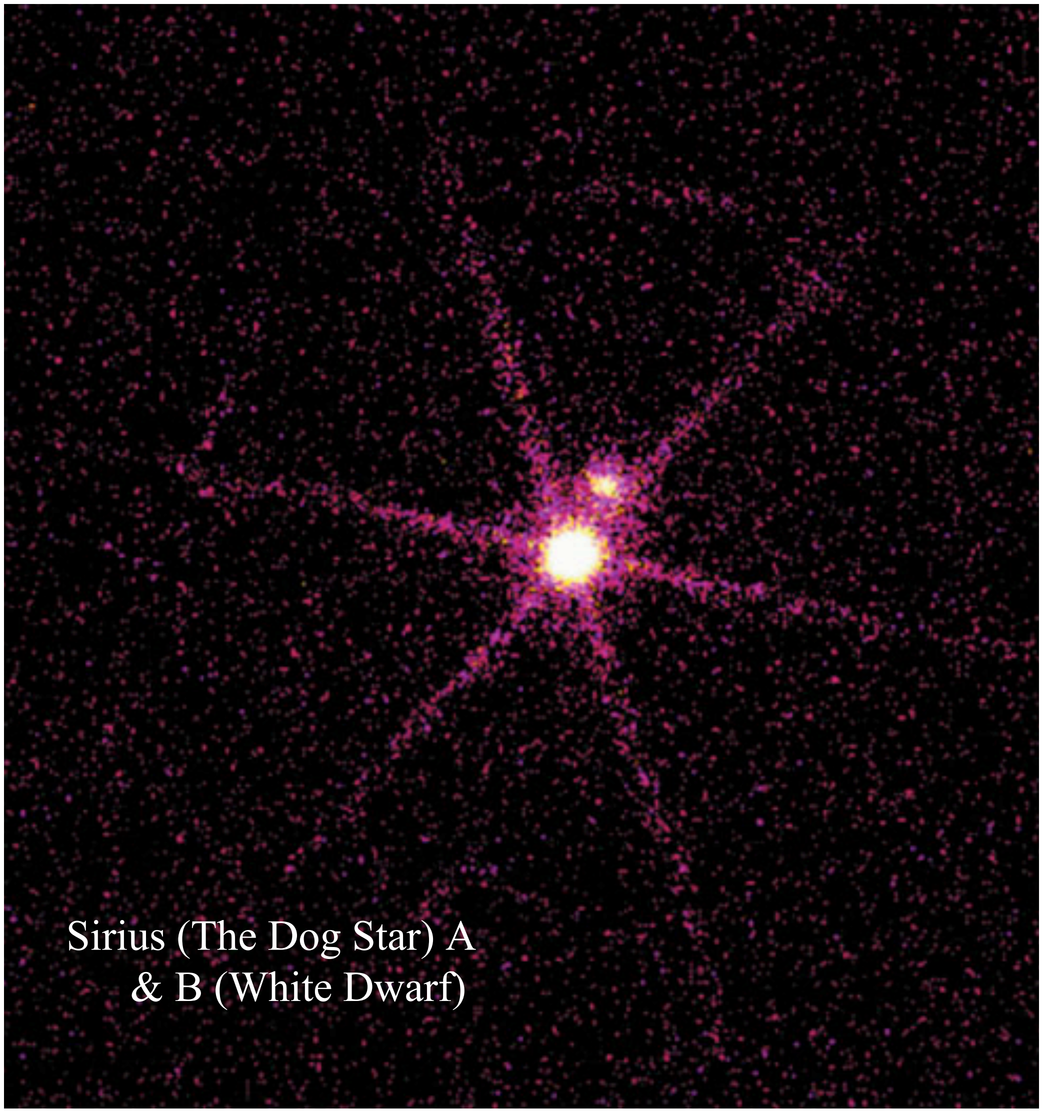
The Stellar Graveyard

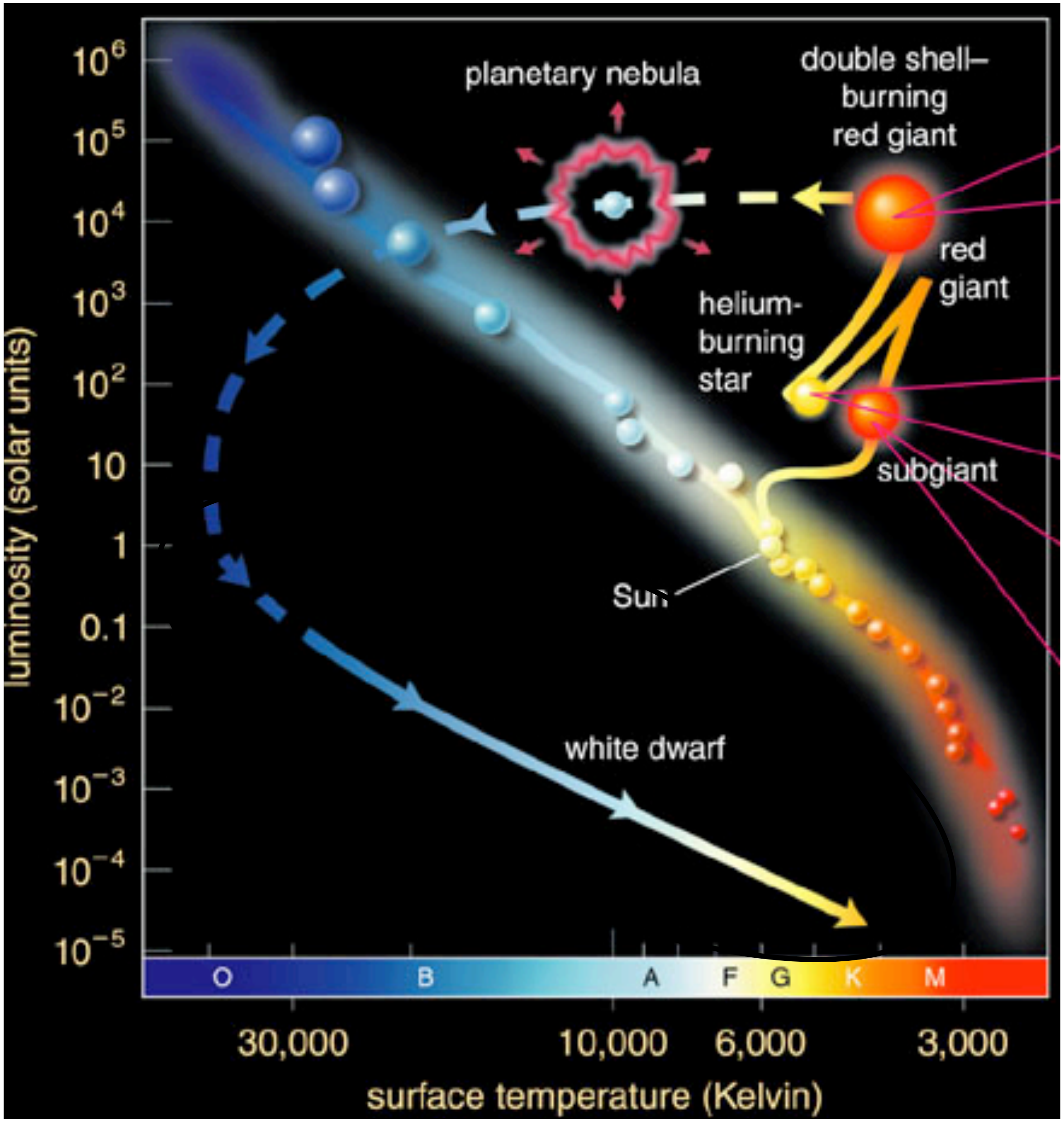
Neutron Stars & White Dwarfs



White Dwarfs

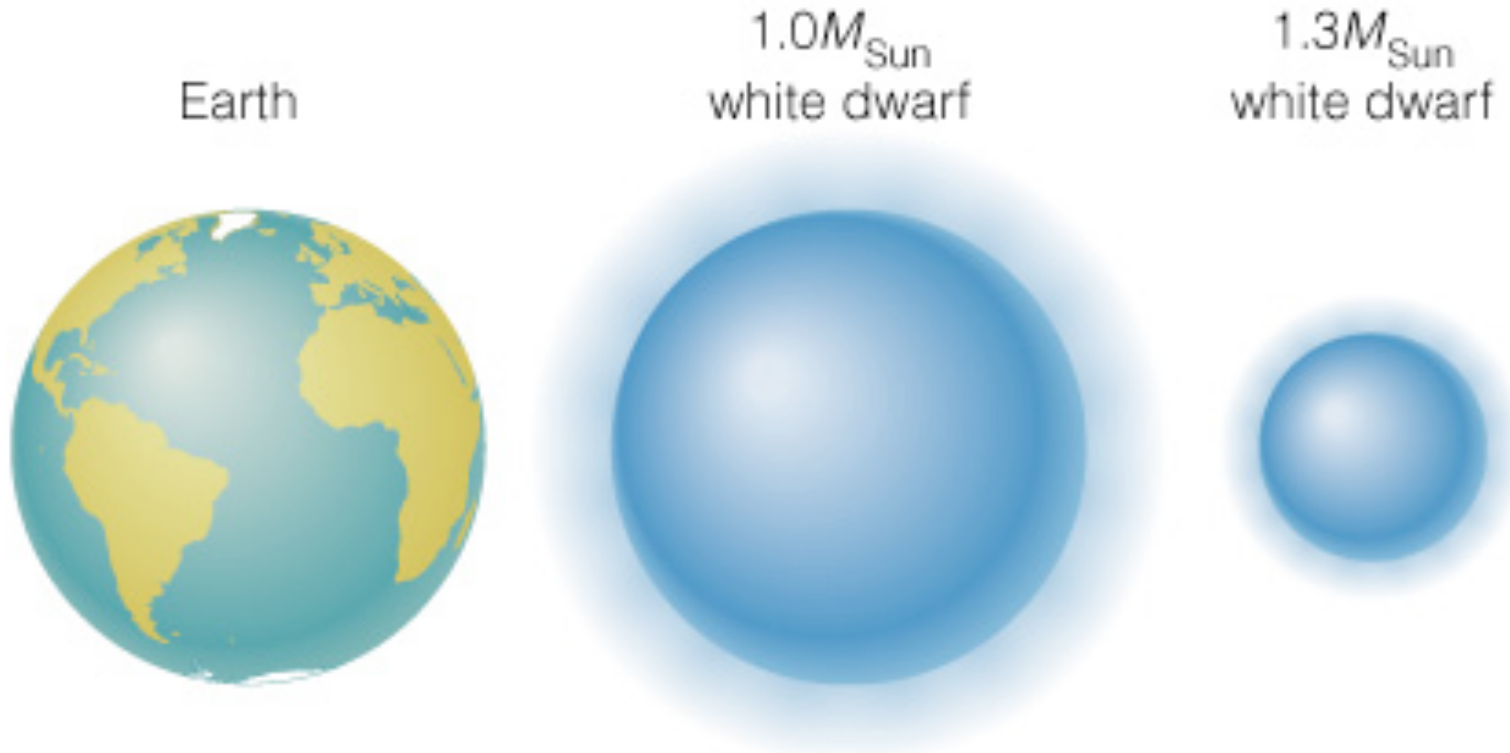


- White dwarfs are the remaining cores of low-mass ($M < 8M_{sun}$) stars
- Electron degeneracy pressure supports them against gravity
- Density ~ 1 ton per teaspoonfull (1 volkswagen/cm^3)
- $R \sim R_{earth}$
- Nuclear reactions have died out; there is no production of energy. (What happens in the H-R Diagram?)



White dwarfs have no means of energy production; they radiate away their store of thermal energy, cool off, and grow dimmer with time.

Size of a White Dwarf

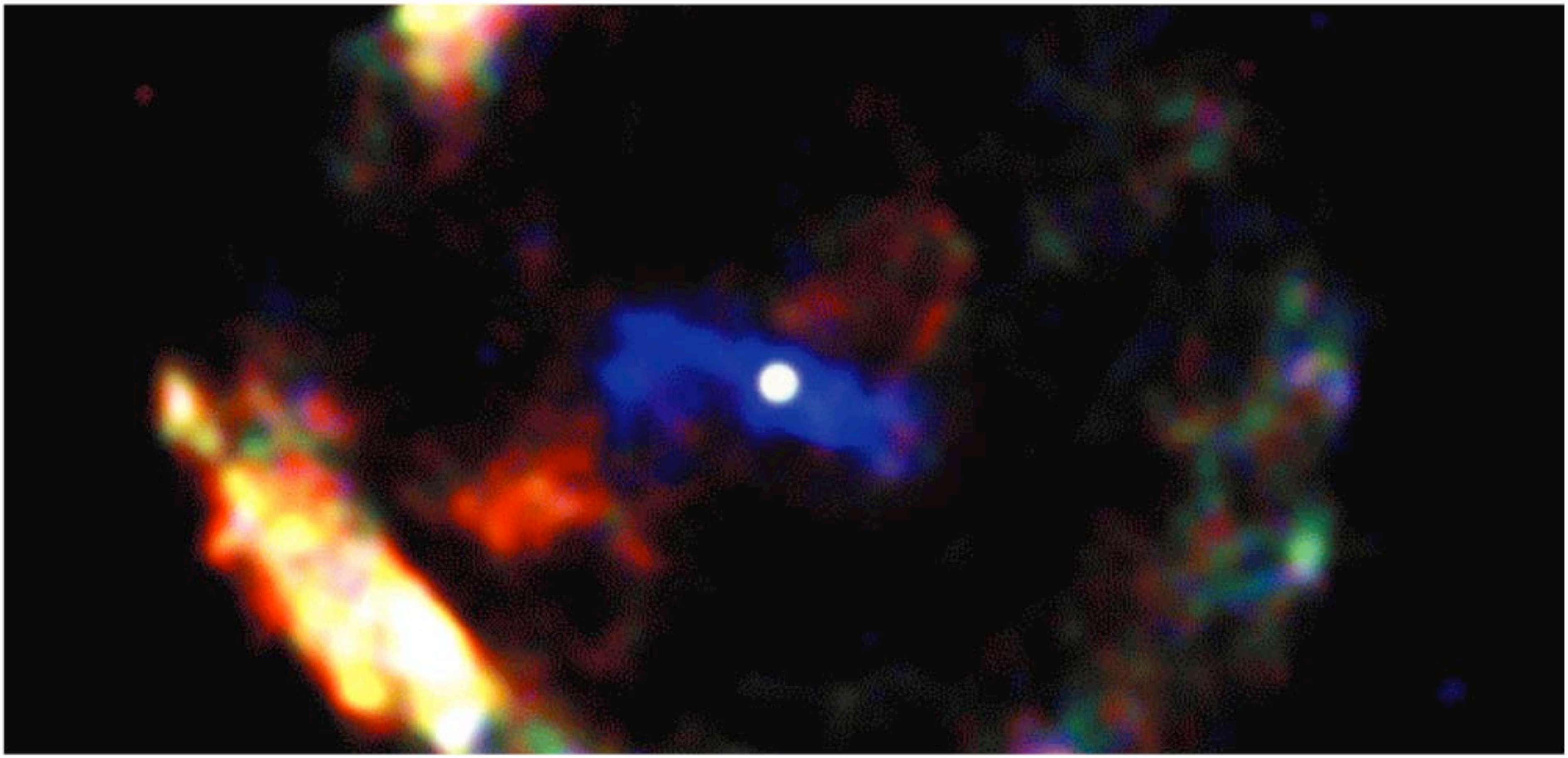


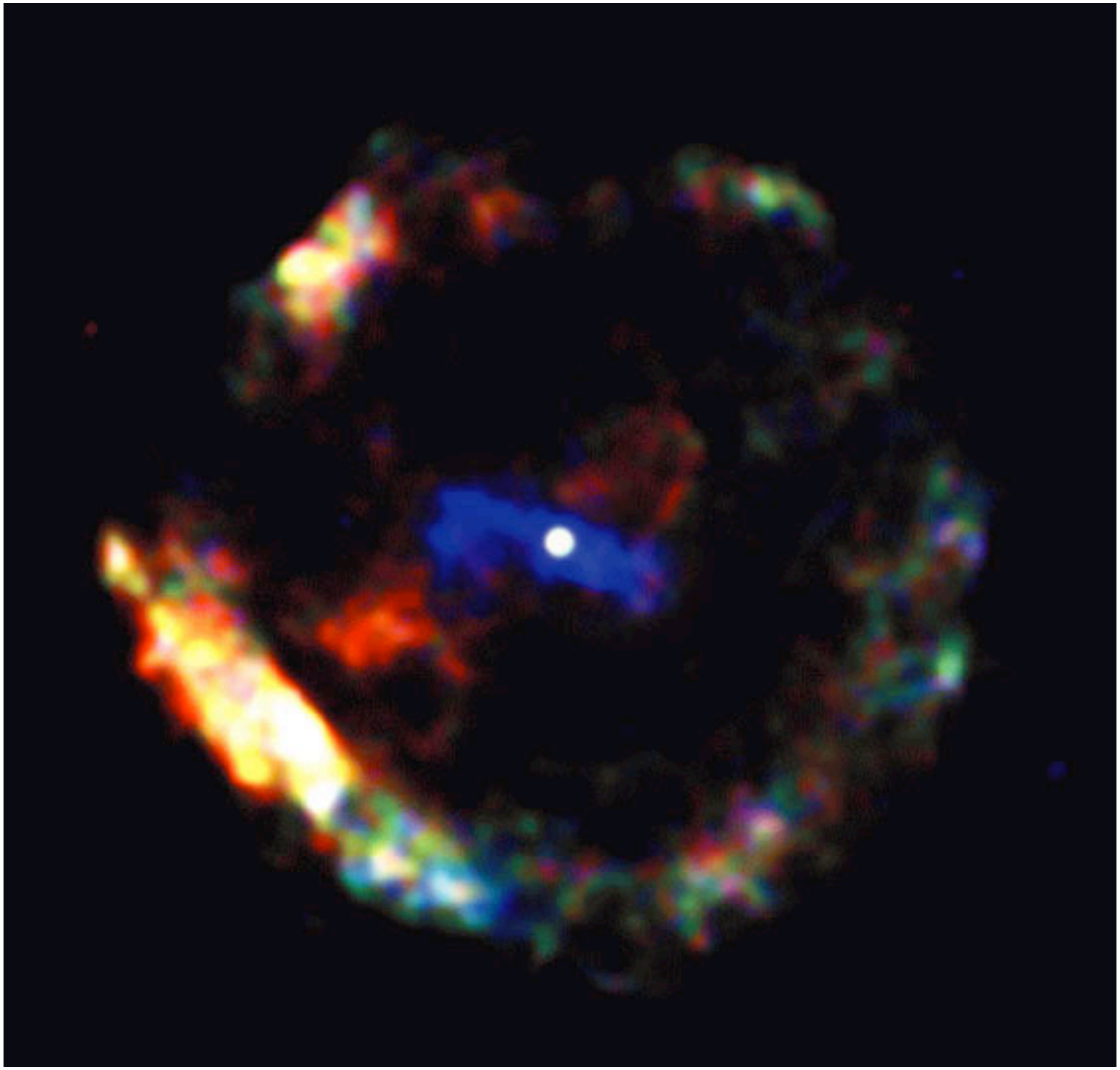
- White dwarfs with same mass as Sun are about same size as Earth
- Higher mass white dwarfs are smaller

The White Dwarf Limit

- Quantum mechanics says that electrons must move faster as they are squeezed into a very small space
- As a white dwarf's mass approaches $1.4M_{Sun}$, its electrons must move at nearly the speed of light
- Because nothing can move faster than light, a white dwarf cannot be more massive than $1.4M_{Sun}$, the *white dwarf limit* (or *Chandrasekhar limit*)

What is a neutron star?



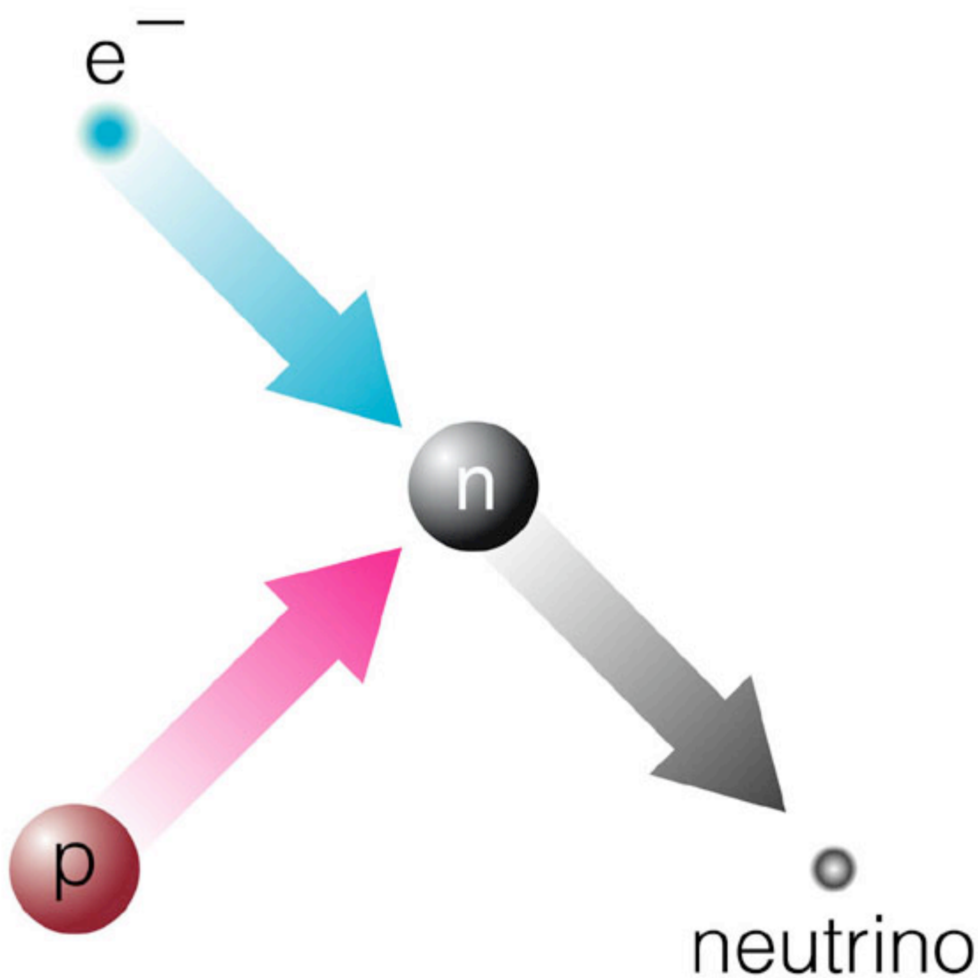


- A *neutron star* is the neutron-rich stellar core left behind by a massive-star supernova

- Degeneracy pressure of *neutrons* supports a neutron star against gravity

- Density ~ 200 million tons per teaspoonfull (all volkswagens/cm^3)

- R ~ 10 km

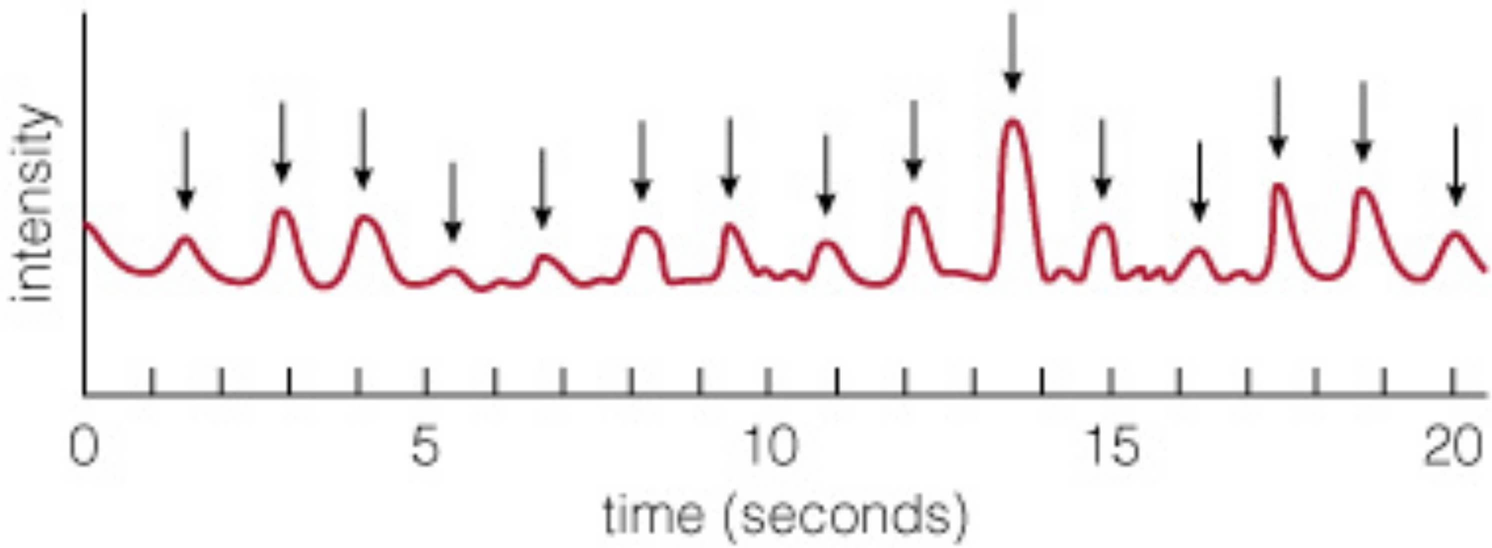


Electron degeneracy pressure goes away because electrons combine with protons, making neutrons and neutrinos in the pre-supernova stellar core

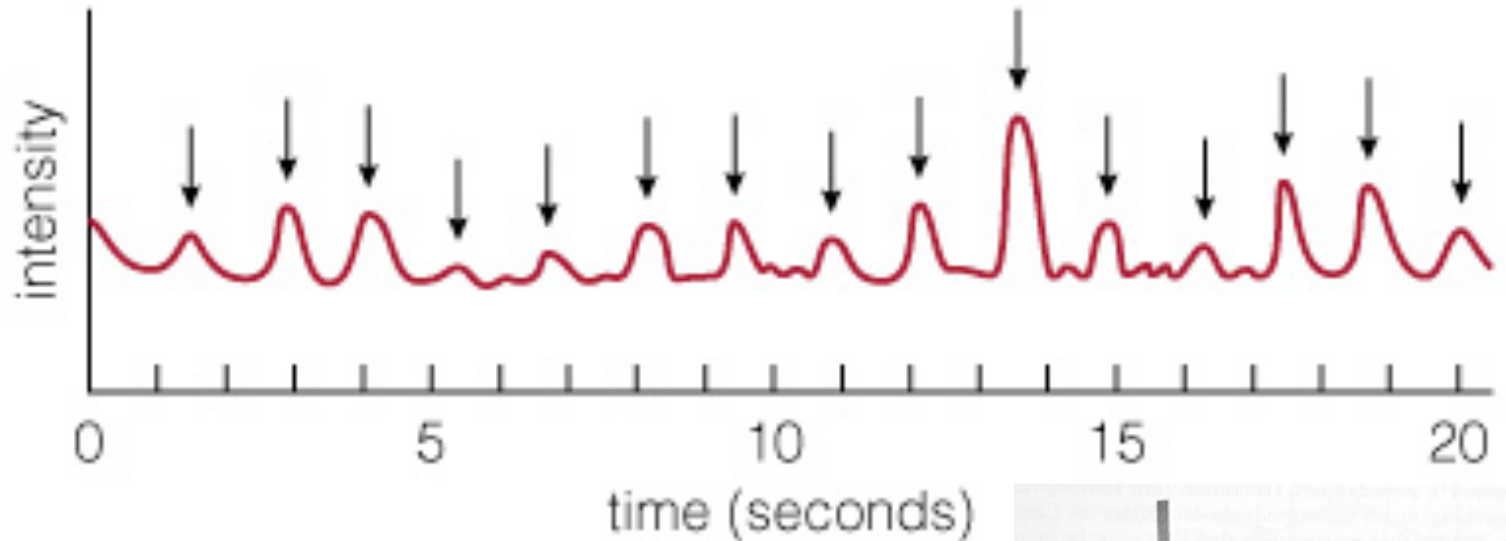
Neutrons collapse to the center, forming a ***neutron star***

A neutron star is about the same size as San Diego

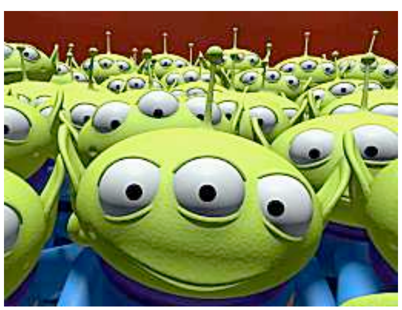
Pulsars



Discovery of Neutron Stars

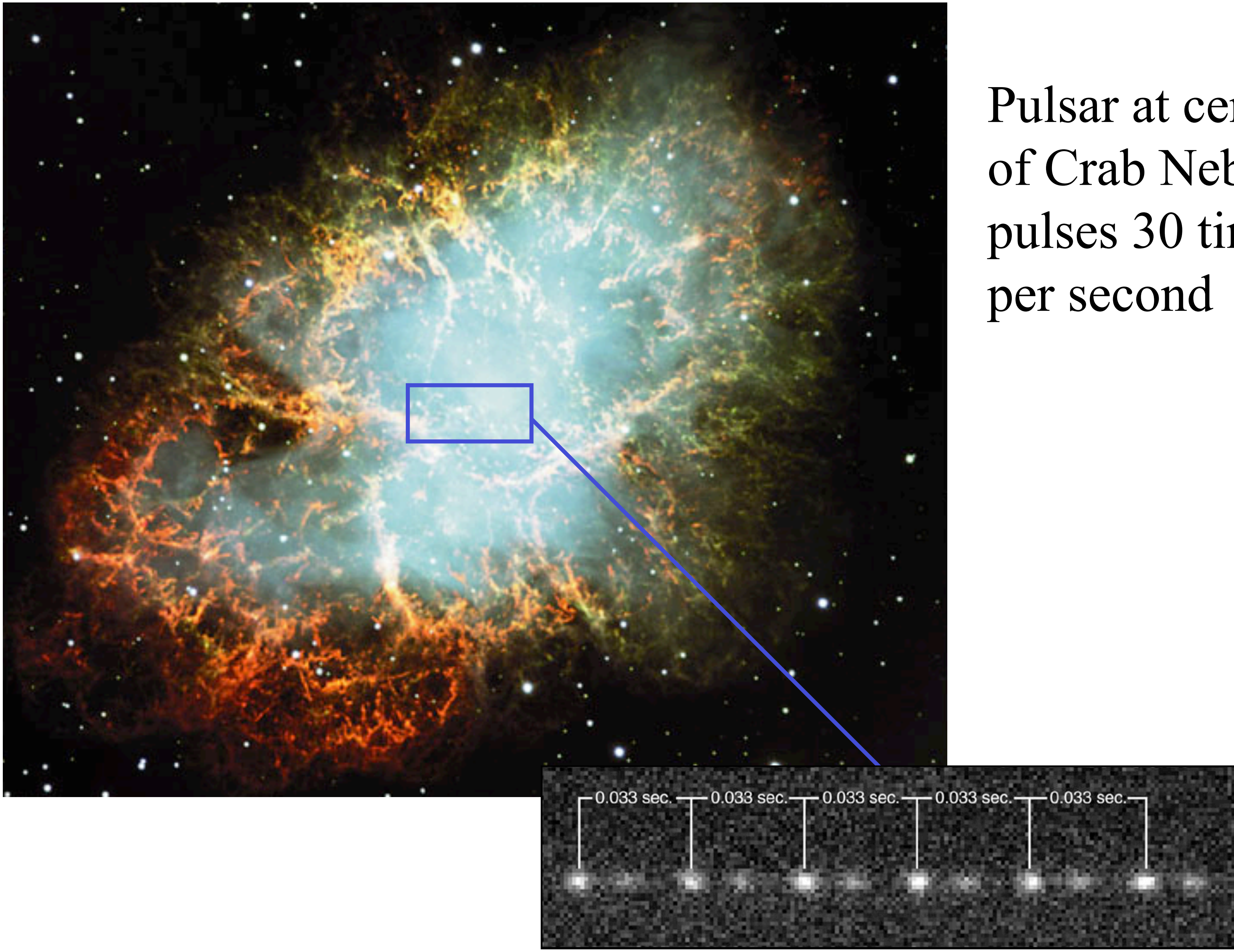


- Using a radio telescope in 1967, Jocelyn Bell noticed very regular pulses of radio emission coming from a single part of the sky



- Originally dubbed "LGM" when more such objects were discovered they were called *pulsars*.

Jocelyn Bell (Burnett) with the Cambridge Phased array that discovered pulsars



Pulsar at center of Crab Nebula pulses 30 times per second

Why Pulsars must be Neutron Stars

Circumference of NS = 2π (radius) ~ 60 km

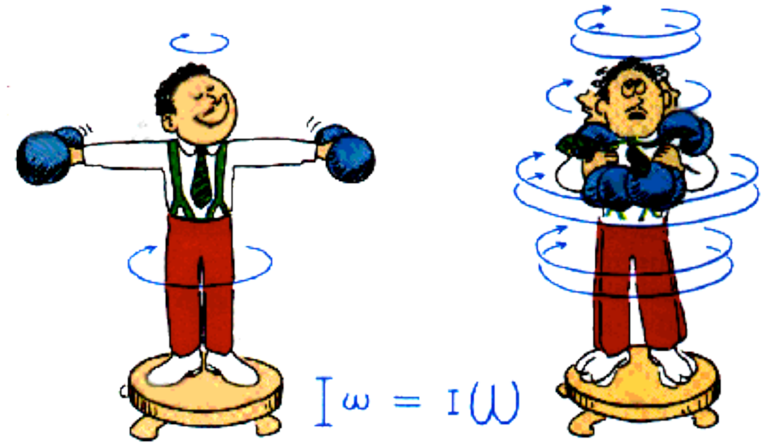
Spin Rate of Fast Pulsars ~ 1000 cycles per second

Surface Rotation Velocity ~ 60,000 km/s
~ 20% speed of light
~ escape velocity from NS

Anything else would be torn to pieces!

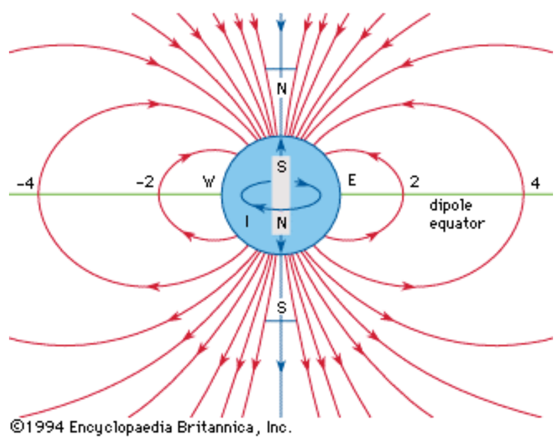
Two Conservation Laws

1. Angular momentum:



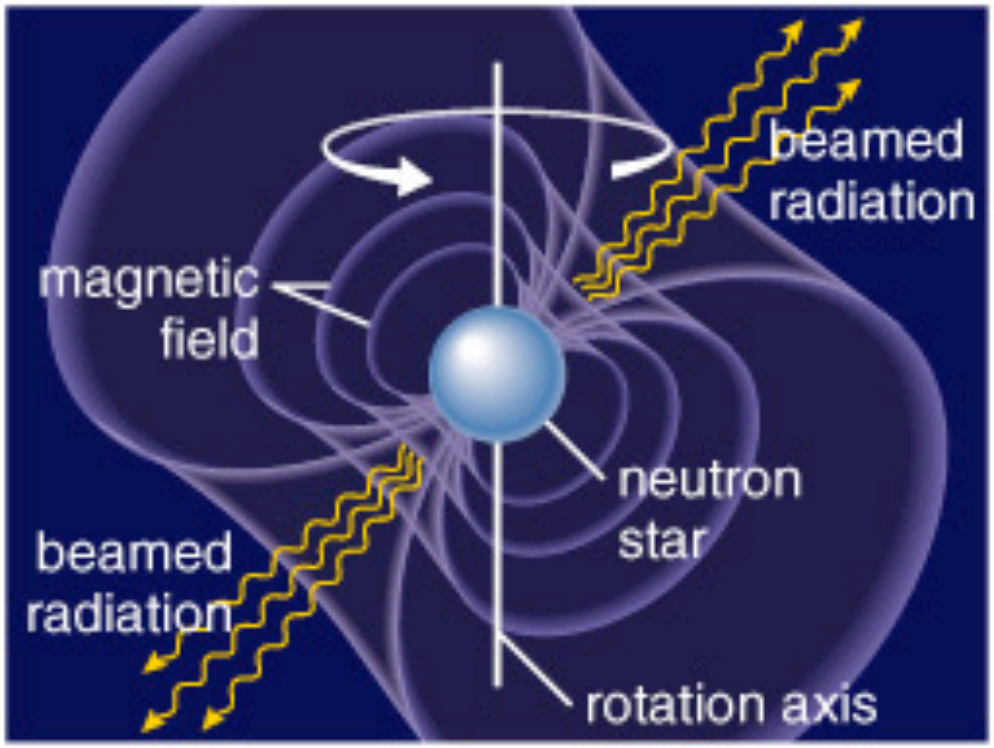
The stellar core shrinks by a factor of over 10,000; this change in "moment of inertia" causes the core to spin-up to ~100 revolutions per second

2. Magnetic flux:



The surface area of the core shrinks by a factor of 100 million or more amplifying the magnetic field strength to $10^{8\text{-}9}$ gauss

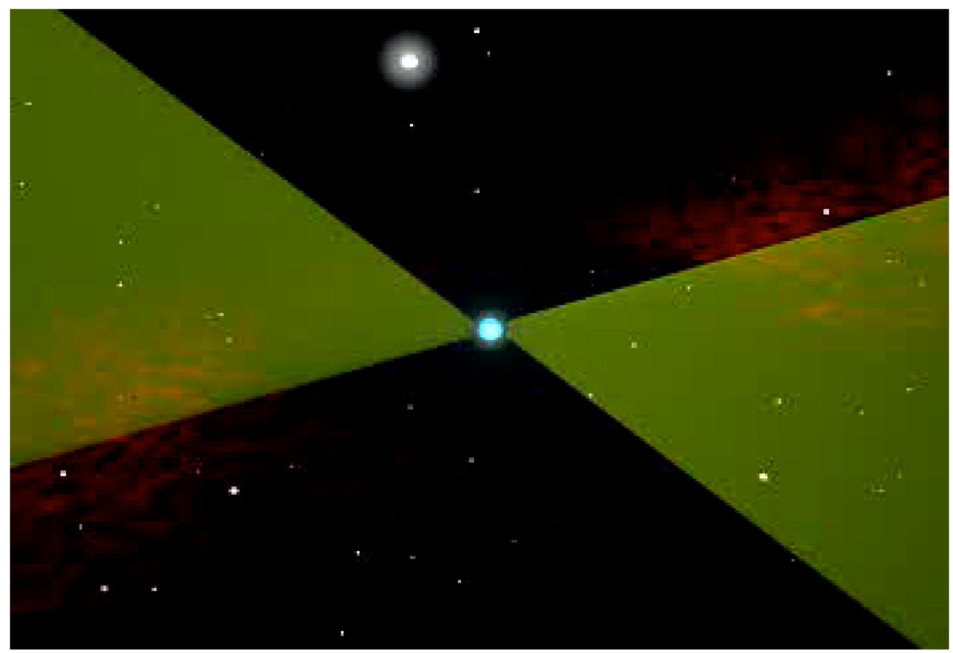
Pulsars



- A pulsar is a neutron star that beams radiation along a magnetic axis that is not aligned with the rotation axis

Pulsars

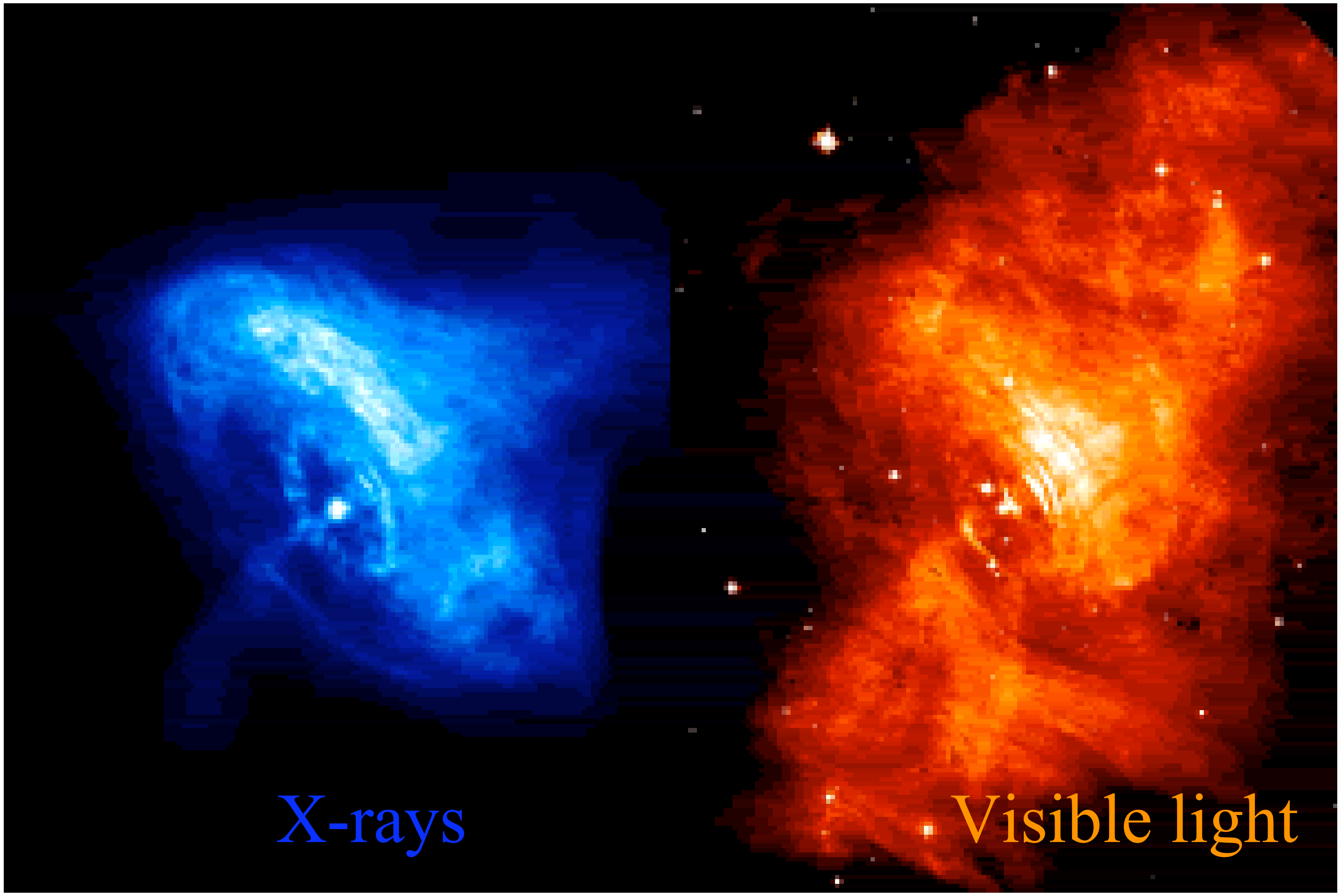
- The radiation beams sweep through space like lighthouse beams as the neutron star rotates



A Great Mystery

Why does the Crab Nebula still shine so brightly (in x-rays, visible light, radio waves …) after nearly a thousand years?

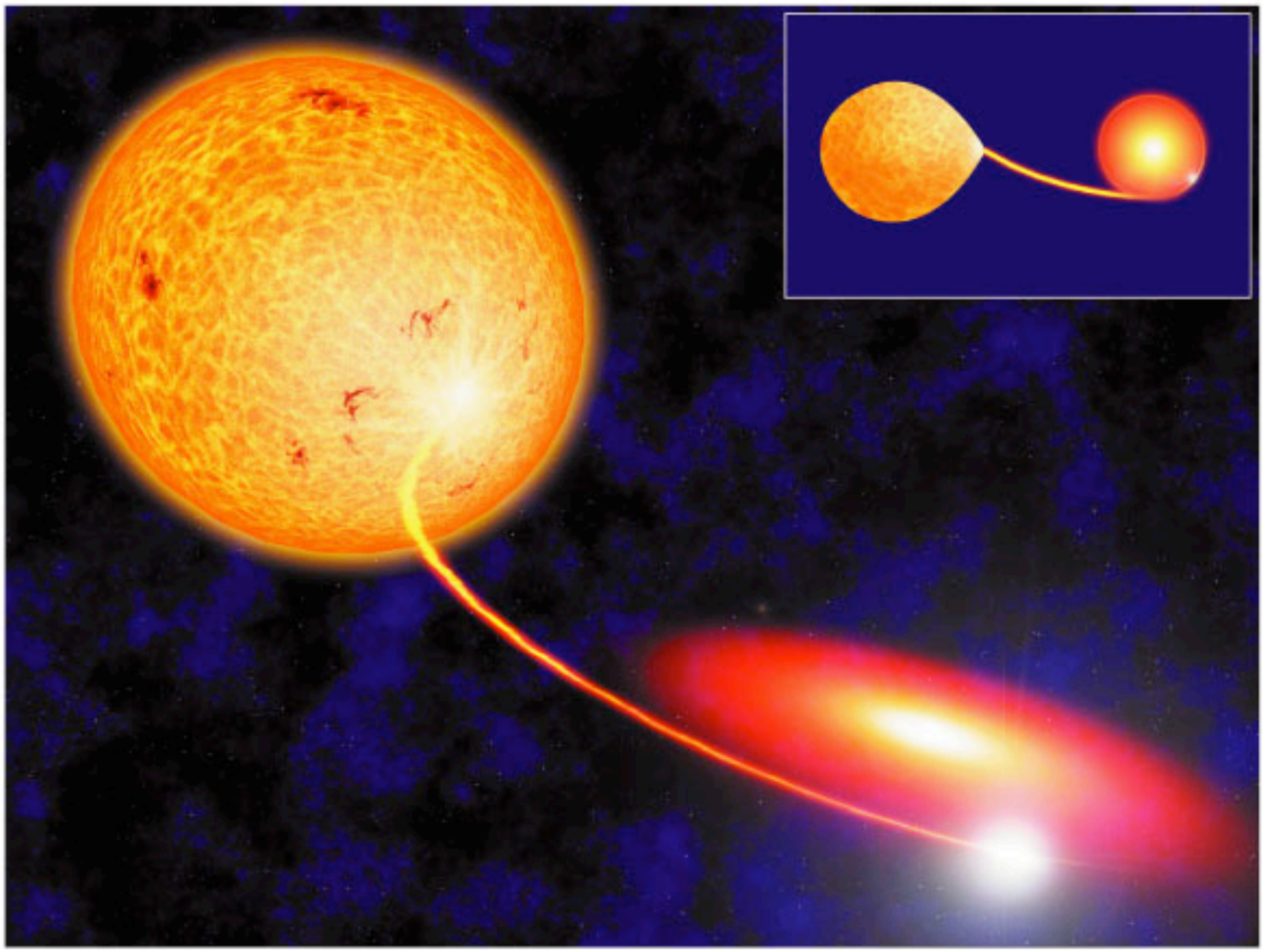
Rotational energy from the Pulsar powers the Crab!

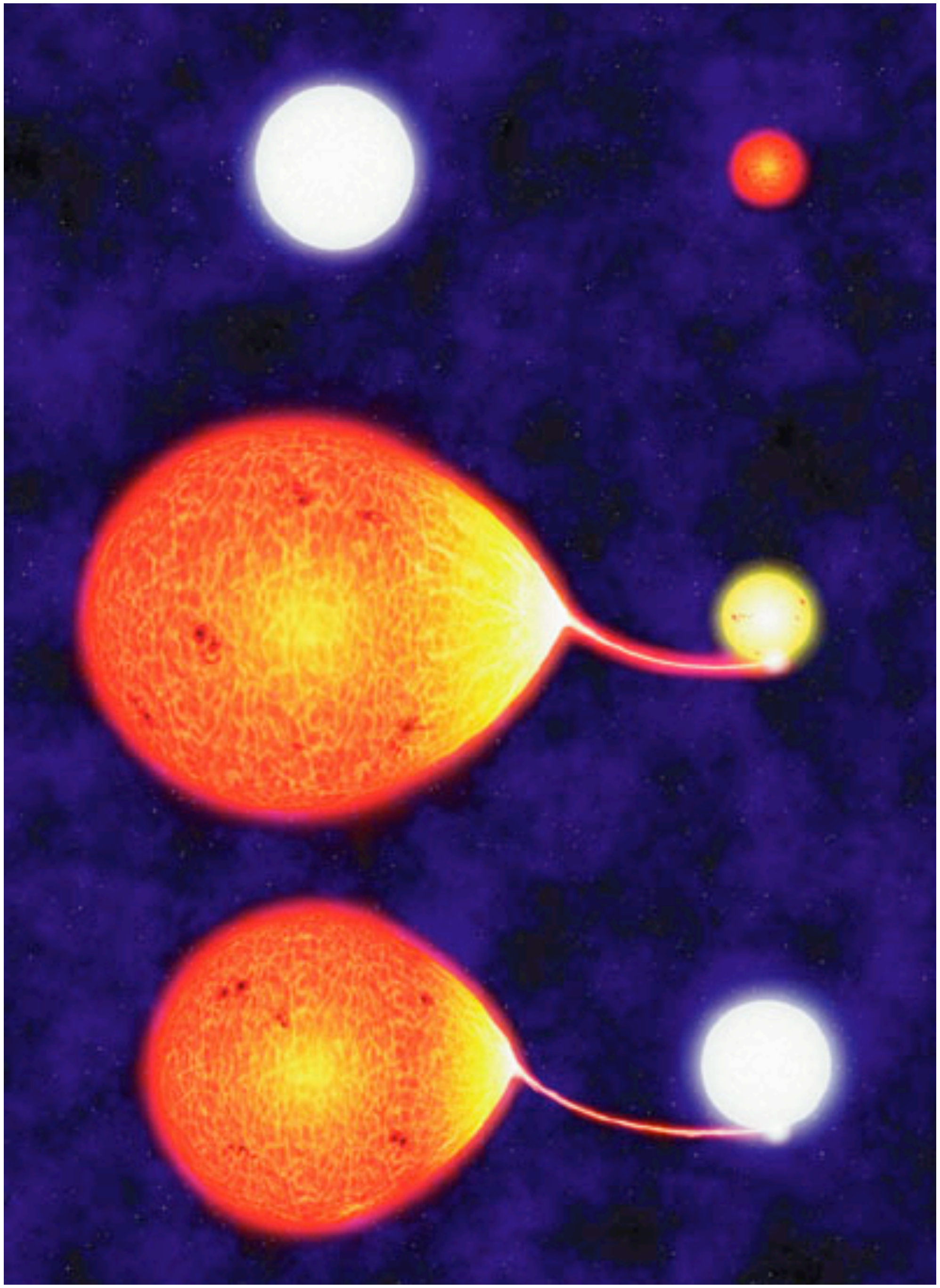


- Interaction between the pulsar’s magnetic field and charged particles in the nebula slows down the pulsar’s spinning

- Low-frequency electromagnetic waves carry energy out into the nebula

What can happen to a white dwarf in a close binary system?



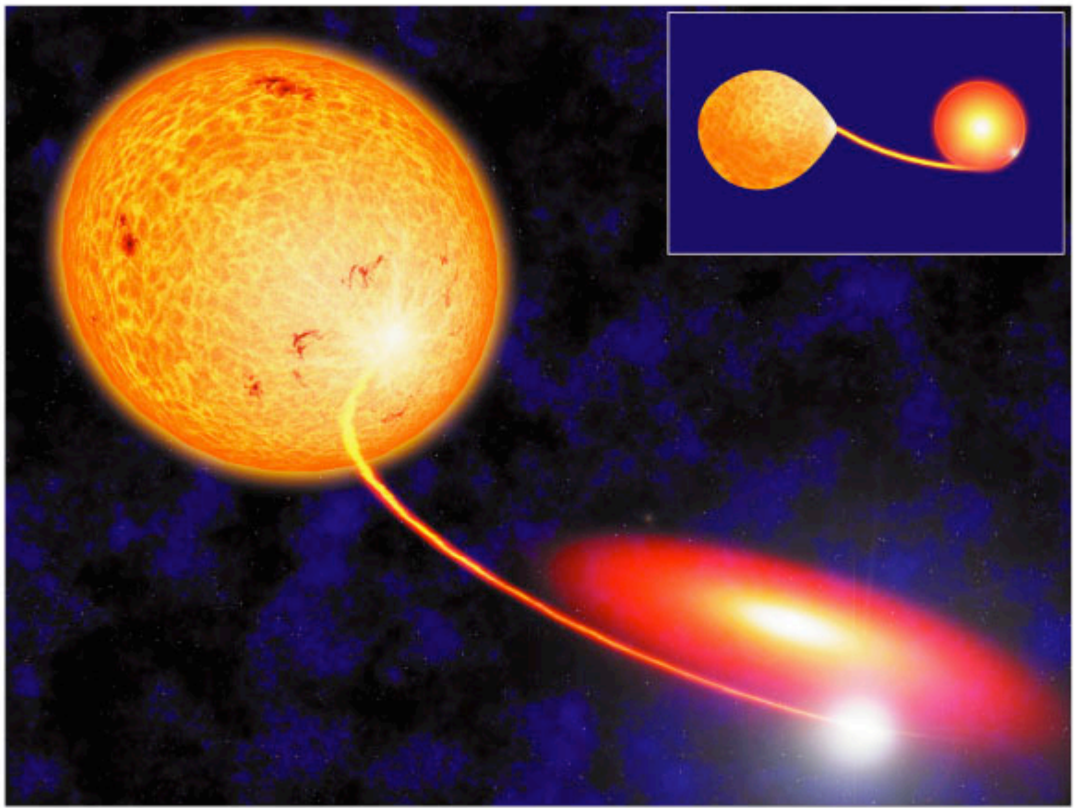


Star that started with less mass gains mass from its companion

Eventually the mass-losing star will become a white dwarf

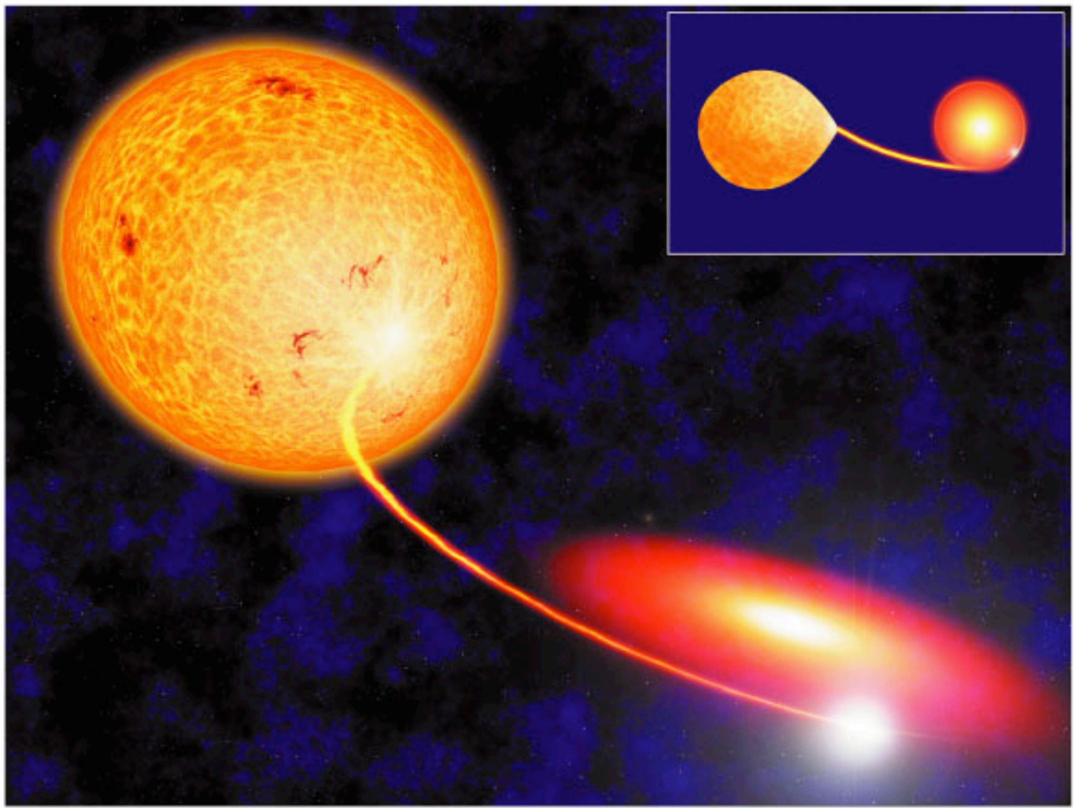
What happens next?

Accretion Disks



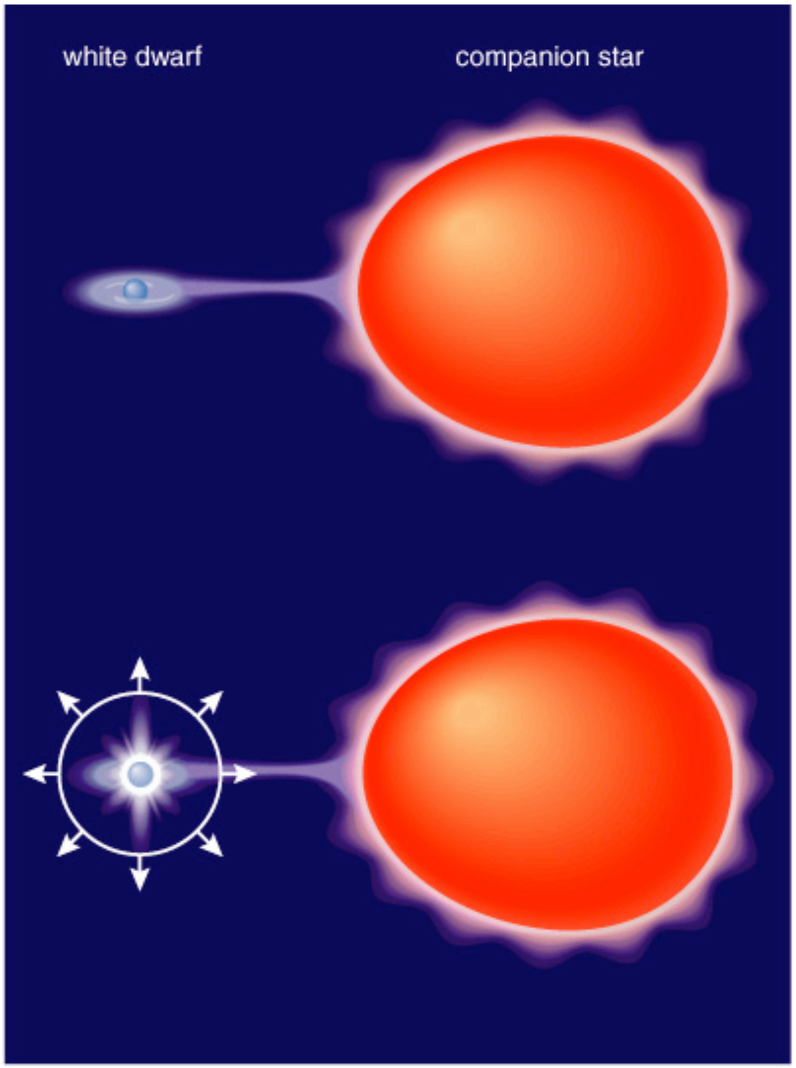
- Mass falling toward a white dwarf from its close binary companion has some angular momentum
- The matter therefore orbits the white dwarf in an *accretion disk*

Accretion Disks



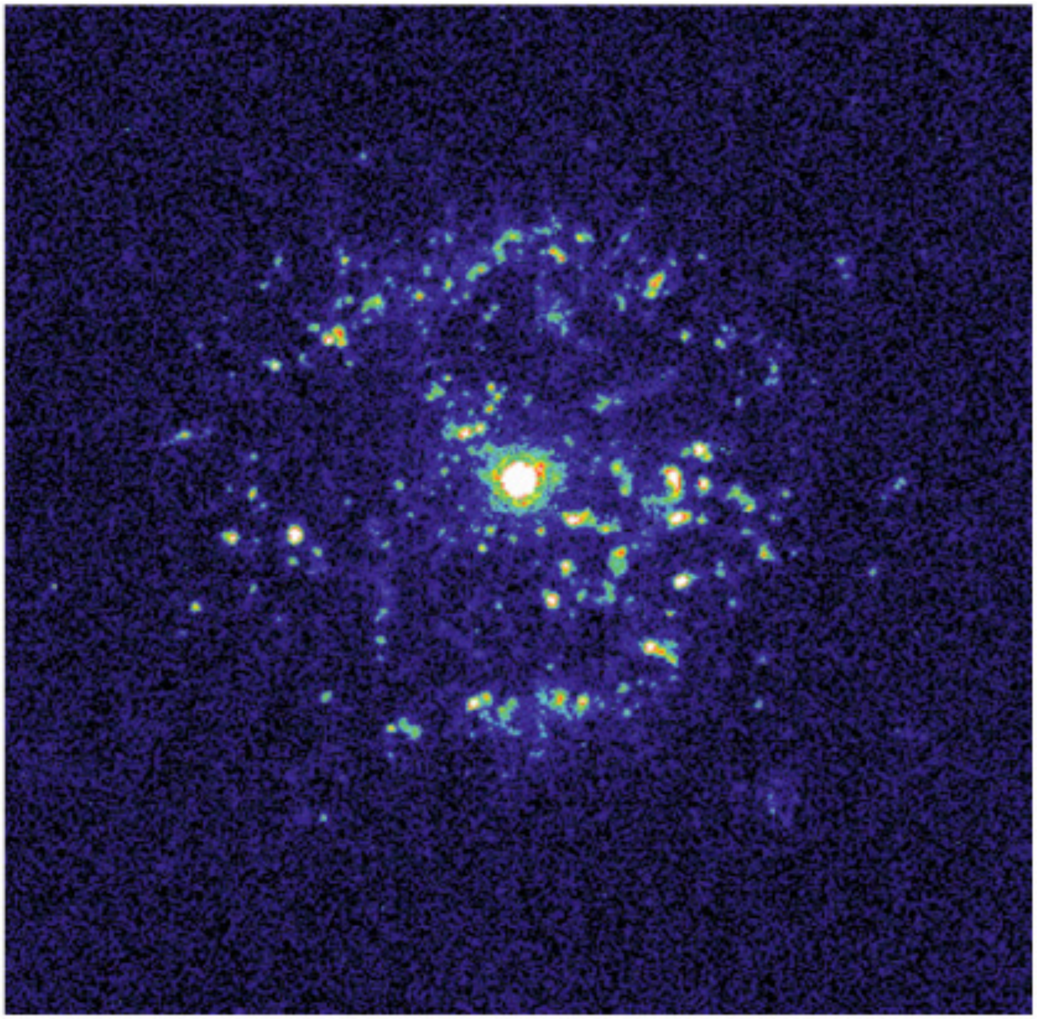
- Friction (*viscosity*) between orbiting rings of matter in the disk transfers angular momentum outward; gravitational energy heats up the accretion disk and causes it to radiate.

Nova



- The temperature of accreted matter eventually becomes hot enough for hydrogen fusion
- Fusion begins suddenly and explosively, causing a *nova*

Nova



- The nova star system temporarily appears much brighter
- The explosion drives accreted matter out into space

Thought Question

What happens to a white dwarf when it accretes enough matter to reach the 1.4 M_{Sun} limit?

A. It explodes
B. It collapses into a neutron star
C. It gradually begins fusing carbon in its core

Thought Question

What happens to a white dwarf when it accretes enough matter to reach the 1.4 M_{Sun} limit?

A. **It explodes**
B. It collapses into a neutron star
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Two Types of Supernova

Massive star (Type II) supernova:

Iron core of massive star reaches white dwarf limit and collapses into a neutron star, causing explosion

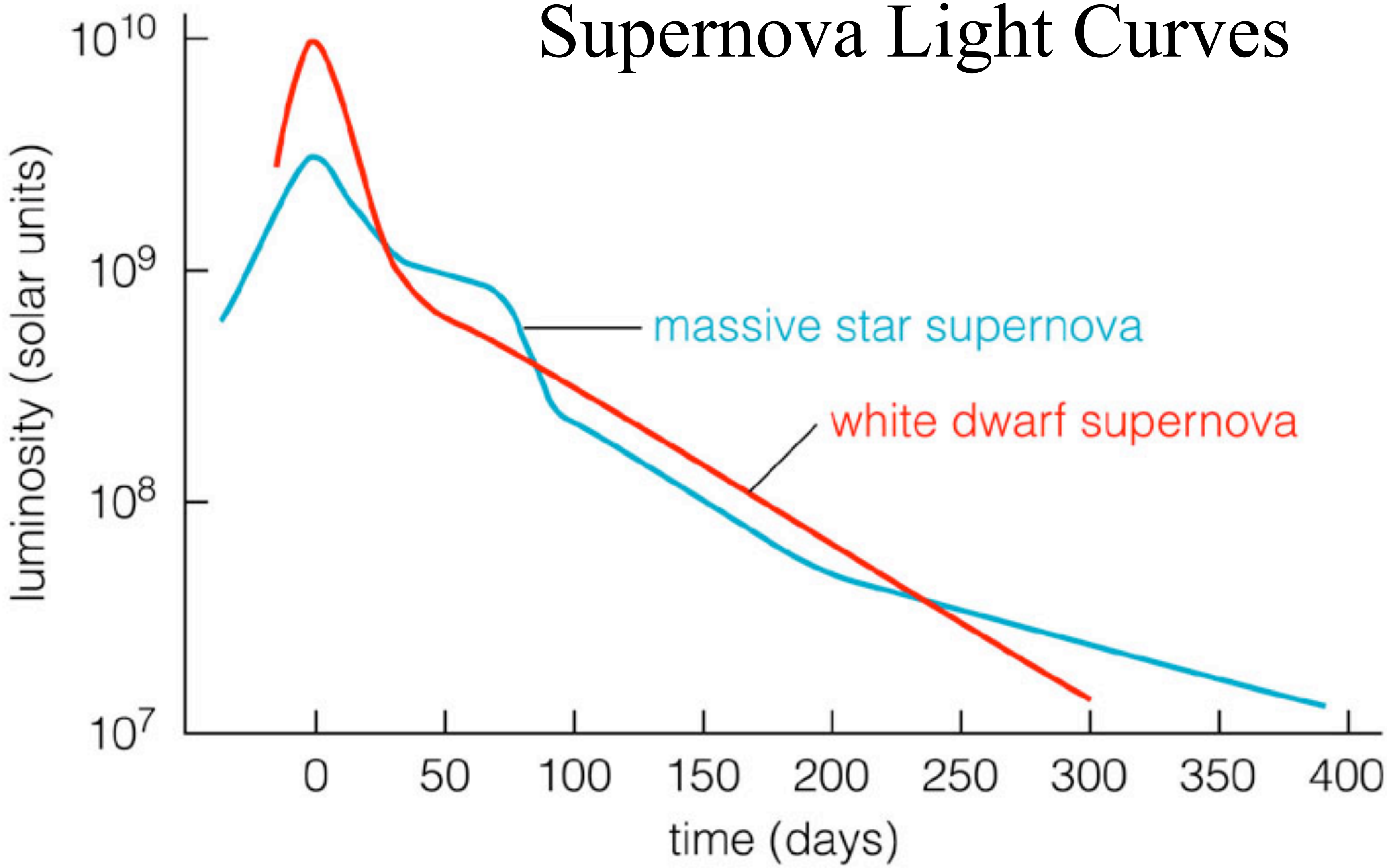
White dwarf (Type Ia) supernova:

Carbon fusion suddenly begins as white dwarf in close binary system reaches white dwarf limit, causing total explosion

Nova or Supernova?

- Supernovae are MUCH MUCH more luminous!!! (about 10 million times)
- Nova: H to He fusion of a layer of accreted matter, white dwarf left intact
- Supernova: complete explosion of white dwarf, nothing left behind

Supernova Light Curves

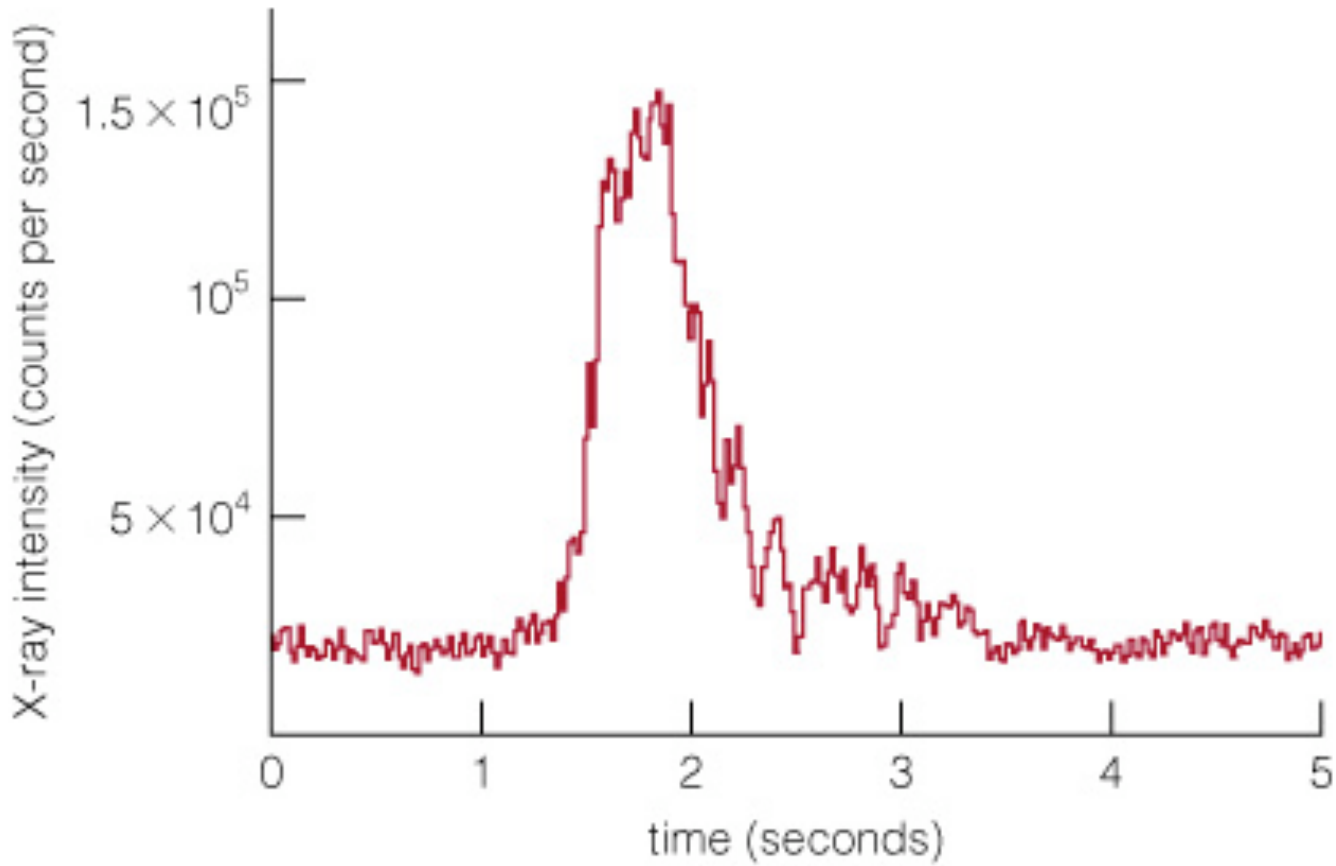


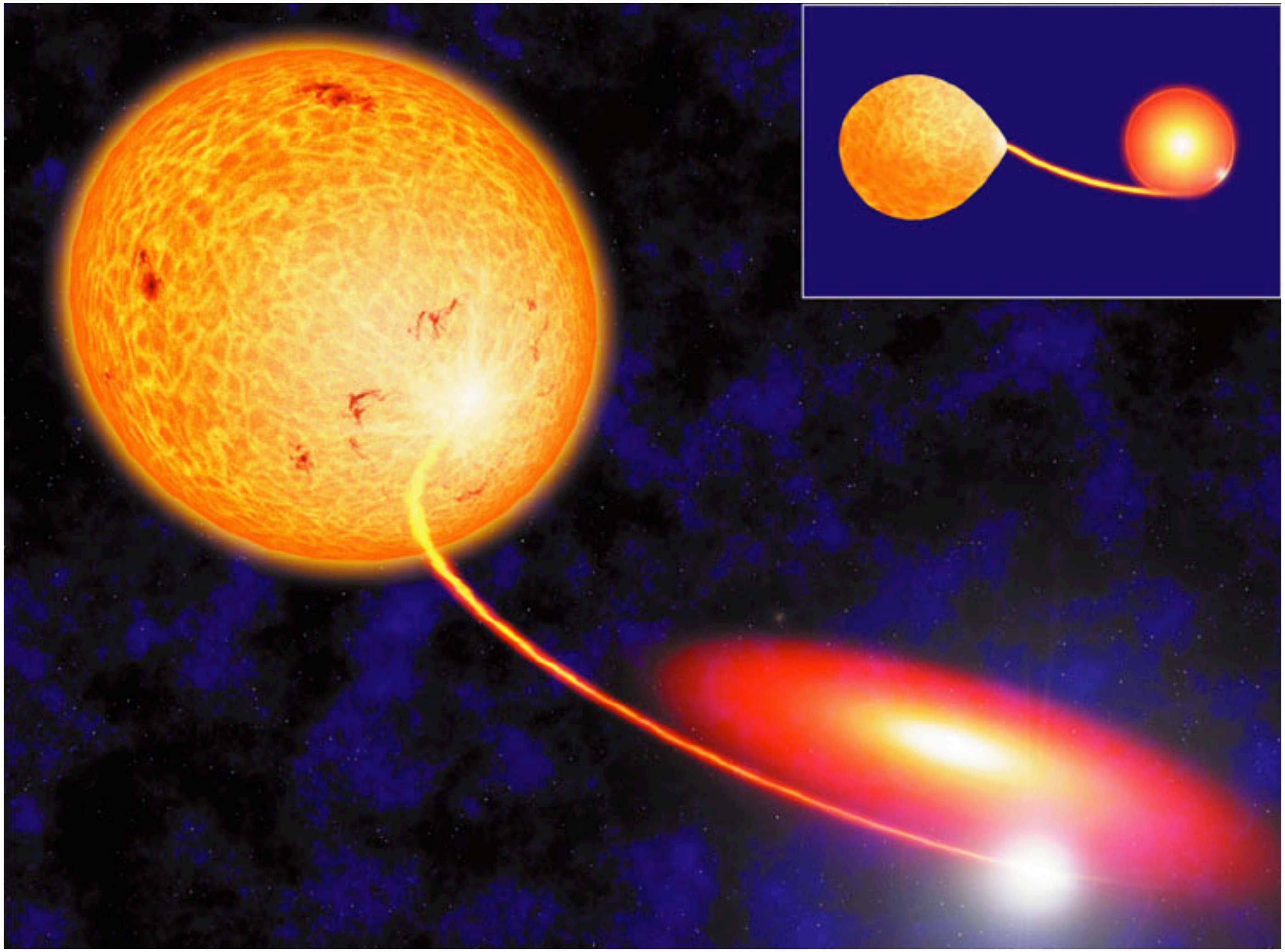
One way to tell supernova types apart is with a ***light curve*** showing how luminosity changes with time

Supernova Type: Massive Star or White Dwarf?

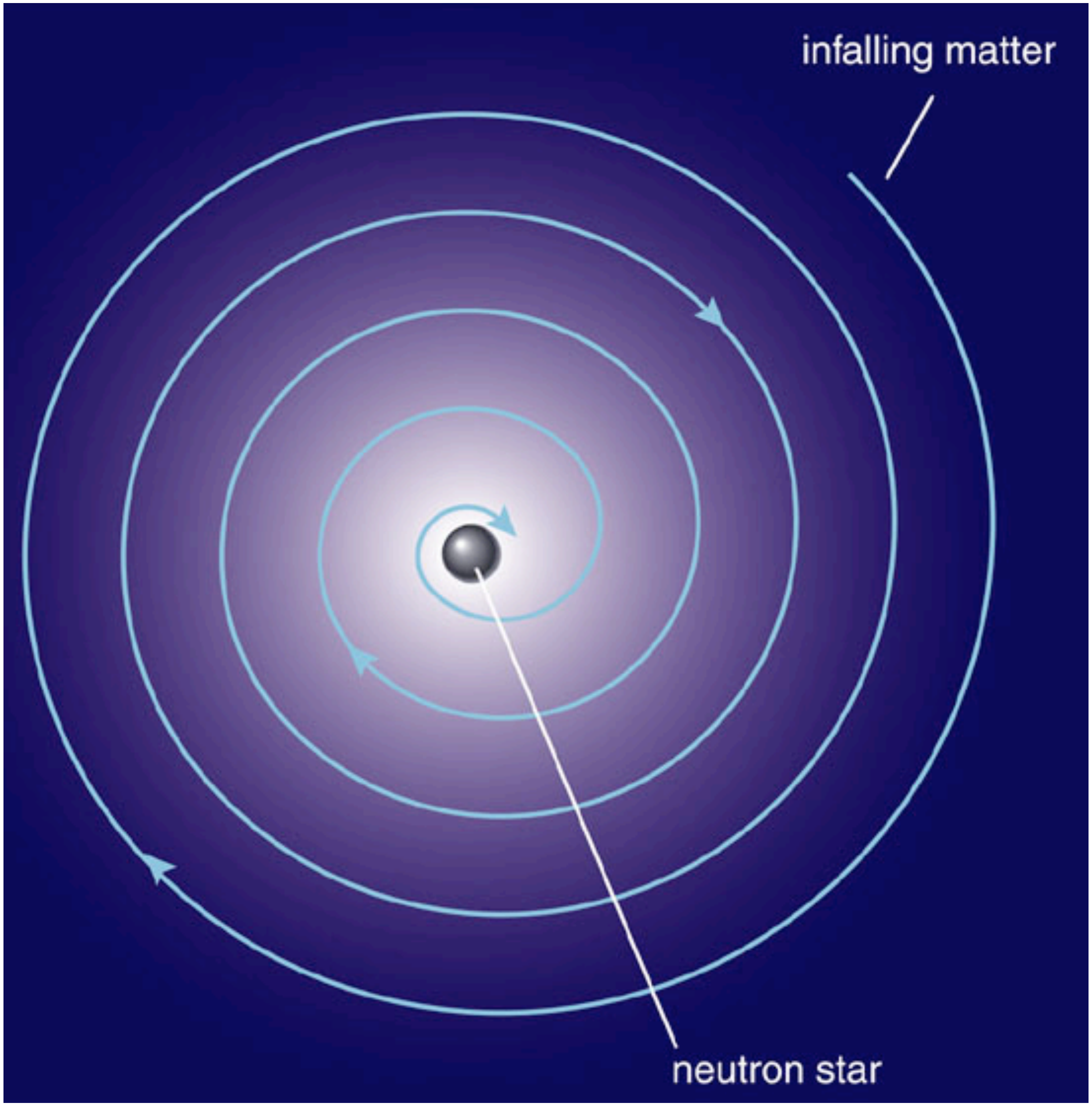
- Light curves differ
- Spectra differ (exploding white dwarfs don't have hydrogen absorption lines)

What can happen to a neutron star in a close binary system?





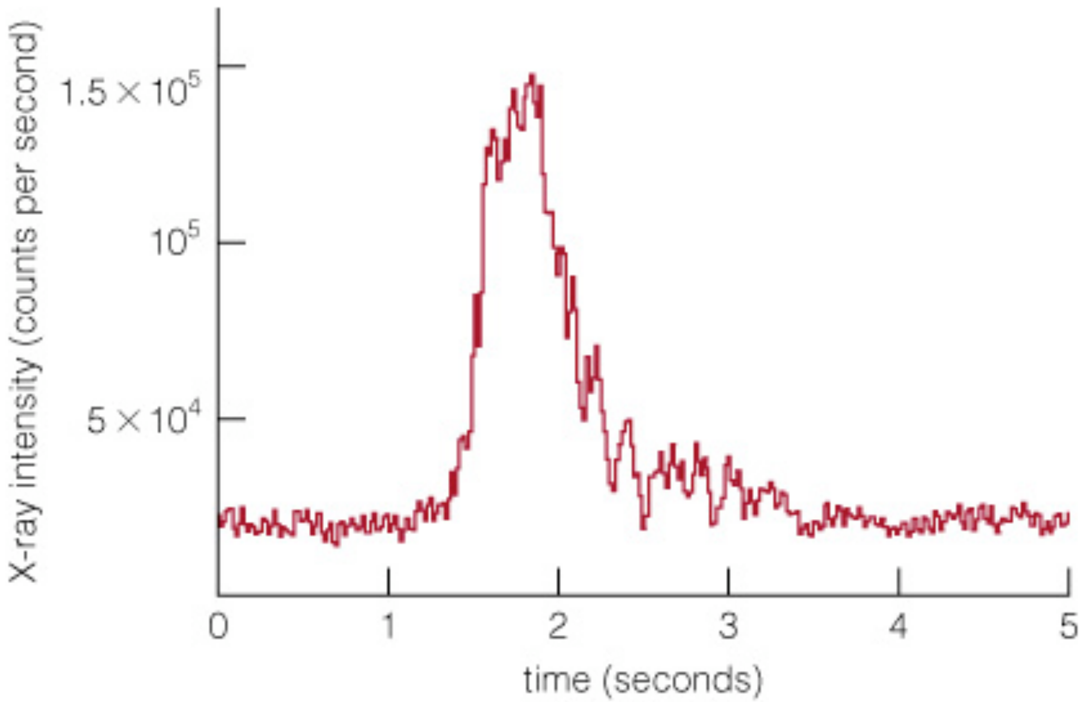
Matter falling toward a neutron star forms an accretion disk, just as in a white-dwarf binary



Accreting matter adds angular momentum to a neutron star, increasing its spin

Episodes of fusion on the surface lead to X-ray bursts

X-Ray Bursts



- Matter accreting onto a neutron star can eventually become hot enough for helium fusion

- The sudden onset of fusion produces a burst of X-rays

What have we learned?

- What is a neutron star?
  - A ball of neutrons left over from a massive star supernova and supported by neutron degeneracy pressure
- How were neutron stars discovered?
  - Beams of radiation from a rotating neutron star sweep through space like lighthouse beams, making them appear to pulse
  - Observations of these pulses were the first evidence for neutron stars

Neutron Star Limit

- Quantum mechanics says that neutrons in the same place cannot be in the same state

- Neutron degeneracy pressure can no longer support a neutron star against gravity if its mass exceeds about 3 M_{sun} (possibly as little as 1.5M_{sun})
- In this case the core must collapse into a remnant of zero size and infinite density - a *black hole*.